A REVIEW OF SCIENTIFIC STUDIES AND THE MANAGEMENT OF NUTRIENT LOADS TO PORT PHILLIP BAY

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The history of the nutrient enrichment of Port Phillip Bay is very much the history of the growth of Melbourne and of the support services developed to manage the collection, treatment and disposal of sewage and industrial wastes. This history is briefly summarised, as is that of the major scientific studies undertaken on Port Phillip Bay. The need to improve our understanding of how Melbourne as a city impacts on the marine environment is seen as an essential part of the on-going program of planning and managing the city's waste disposal system.

PORT PHILLIP BAY, a large, shallow marine embayment with restricted exchange to Bass Strait, is an integral part of the Melbourne environment and represents a major asset which is important to the prosperity and well-being of the city as well as to the rest of the State. The Bay is important because of the opportunities it offers in terms of recreation, tourism, commercial fishing, mariculture, transport and shipping, urban scenic value, cooling water, and as a receiving environment for urban and industrial wastes and dredge spoil. The economic worth of the Bay is illustrated in a simple way by the following figures for the value of its fisheries (Bremner et al. 1989).

Commercial fishing	\$50–80 million	(1986)
Recreational fishing	\$250 million	(1982)

The disposal to the Bay of sewage, other domestic waste and dredge spoil is not recognized as a "beneficial use" under the Victorian Environment Protection Act. Nevertheless, the development of the city and its adjacent suburban and industrial assets over the last 160 years has taken place by using the Bay as a cost-effective mechanism for the disposal of waste materials. The wastes include plant nutrients which, when present in "excess", have been shown to cause major changes in water quality and biological systems (e.g. Cambridge 1975, Cambridge et al. 1986, Silberstein et al. 1986, Chiffings & McComb 1981, Simpson et al. 1990). The capacity of the Bay to continue to assimilate or accommodate these materials is a key question that needs to be addressed in future scientific assessments of the Bay.

MELBOURNE'S IMPACT ON THE BAY

Prior to settlement of the region by Europeans, inputs of nutrients to the Bay from land-based sources would have been part of a natural process of addition, recycling and loss that occurs in all coastal waters. These processes in conjunction with natural physical and biological characteristics would have dictated the net productivity of Port Phillip Bay.

The process of nutrient addition has now been greatly enhanced by urban, industrial and agricultural activities within the catchment over the last 150 years. In a developed catchment, plant nutrients come from sewerage discharges, urban run-off, clearing of the catchment, agricultural activities, emergency sewerage overflows, unsewered properties and industrial wastes. Depending on the degree of increase in net production prompted by the addition of nutrients from such sources, the effects on a coastal system may be beneficial or detrimental (Mann 1982). The history of this "cultural" nutrient enrichment of Port Phillip Bay reflects the history of the growth of Melbourne itself.

The settlement on the banks of the Yarra had a resident population of some 200 when it was named Melbourne by Governor Bourke in March 1837 (Grant & Serle 1983). Melbourne's subsequent growth was rapid and by 1841 the population was estimated at 6,000. The Yarra was both water supply and sewer, and the town became notorious world-wide for its high death rate through cholera and dysentery. By 1858 the problem of water supply had been addressed with the construction of Melbourne's first dam at Yan Yean on the Plenty River (Dingle & Rasmussen 1992).

Sanitary conditions in the town were very poor, as reflected by a survey undertaken by Clement Hodgkinson in 1852 for a Select Committee on the Sewerage and Supply of Water for Melbourne. He found that "in backyards and enclosures, more astounding accumulations of putrescent substances and rubbish of all kinds, than I ever inspected in the very worst parts of dirtiest English and Continental towns . . . Many of the foundations of the buildings were greatly injured owing to the saturation of the subsoil by liquid excrementitious matter" (Grant & Serle 1983). This situation, combined with the establishment of tallow rendering plants on the banks of the Yarra, led to a severe degradation of the water quality of the river (Seeger 1961) and, presumably, of parts of the Bay.

Such conditions prevailed for an additional 45 years before the Melbourne sewerage system was commissioned by the Melbourne and Metropolitan Board of Works (MMBW, now Melbourne Water), established in 1891. By 1899, the population of Melbourne was estimated at 477,790 and 32% of the 105,000 tenements were connected to the sewerage system (Seeger 1961).

The rate of progress in sewering Melbourne over the intervening 93 years varied, with a consequent impact on the water quality of Melbourne's urban streams and the Bay. As recently as 1970 the Senate Select Committee on Water Pollution documented an extremely poor situation in and around Melbourne, with ambient water quality influenced by sewerage and industrial waste discharges. Since then, progressive action has ensured considerable improvements in the water quality of urban streams (Bremner et al. 1989). These improvements are due to State initiatives resulting in the establishment of the Victorian Environment Protection Authority (EPA), and to the National Sewerage Program established by the Federal Government in the 1970s. A total of $88,290,816 (historic dollar values) was spent by Melbourne Water from the National Sewerage Program over the period 1973–77, leading to a considerable decrease in the backlog of properties to be sewered.

The introduction of EPA licence requirements for discharges to waterways and drains also had an impact, leading to improvements in discharge quality, the termination of discharges, or their diversion to the sewer. In their role as a delegated agency for the EPA, Melbourne Water used data from Phase 1 of the Environmental Study of Port Phillip Bay (see below) in setting licence conditions for discharges. The EPA used the physico-chemical data and recommendations from the study in preparing the State Environment Protection Policy (SEPP) for the Waters of Port Phillip Bay.

Although trade waste discharges were first accepted into the sewer in 1945, after the establishment of the EPA in 1970 there has been an increasing trend for industrial wastes to be diverted away from urban streams and the Bay and into the sewerage system. At present, trade waste discharges account for 17.5% of the average daily flow of 504 ML and 48% of the biochemical oxygen demand (BOD) load to the Werribee Treatment Complex (WTC; Fig. 1), which discharges the treated waste water to Port Phillip Bay. In contrast, trade waste discharges account for only 6.3% of the average daily flow of 361 ML and 21% of the BOD load to the Carrum Treatment Complex, which discharges to Bass Strait.

With an estimated resident population (at June 1990) of 2,585,000 living in 997,390 properties, 98% of which are connected to the sewerage system (MMBW 1990a), Melbourne now has a well-established hydraulic infrastructure for the management of its domestic wastes and much of its industrial wastes. Strong design principles laid down by James Mansergh in 1890 have led to this system having served the city for 100 years (Dingle & Rasmussen 1991). While considerable additions and improvements have been made to the original system in order to service the growth of Melbourne, much of it is still in use.

Principal features of the system are the use of land treatment located at a site consistent with the anticipated growth pattern and population of the metropolis, separation of surface drainage from sewage collection, and an initial investment in infra-structure which was designed to service a community of 1.7 million at a time when the population was less than 500,000. In June 1990 dollar values the initial capital investment in the system in 1900 was $198 million. In comparison, the worth of these capital assets as developed over the 90 year period was estimated in June 1990 at $1.8 billion (MMBW 1990a).

About 93% of the sewage flow from Melbourne was treated by the WTC system prior to the commissioning of the Carrum Treatment Complex in 1975. During 1988/89, approximately 179,000 ML or 60% of the annual flow from Melbourne was treated at Werribee. The facilities include treatment of 16% of the flow by

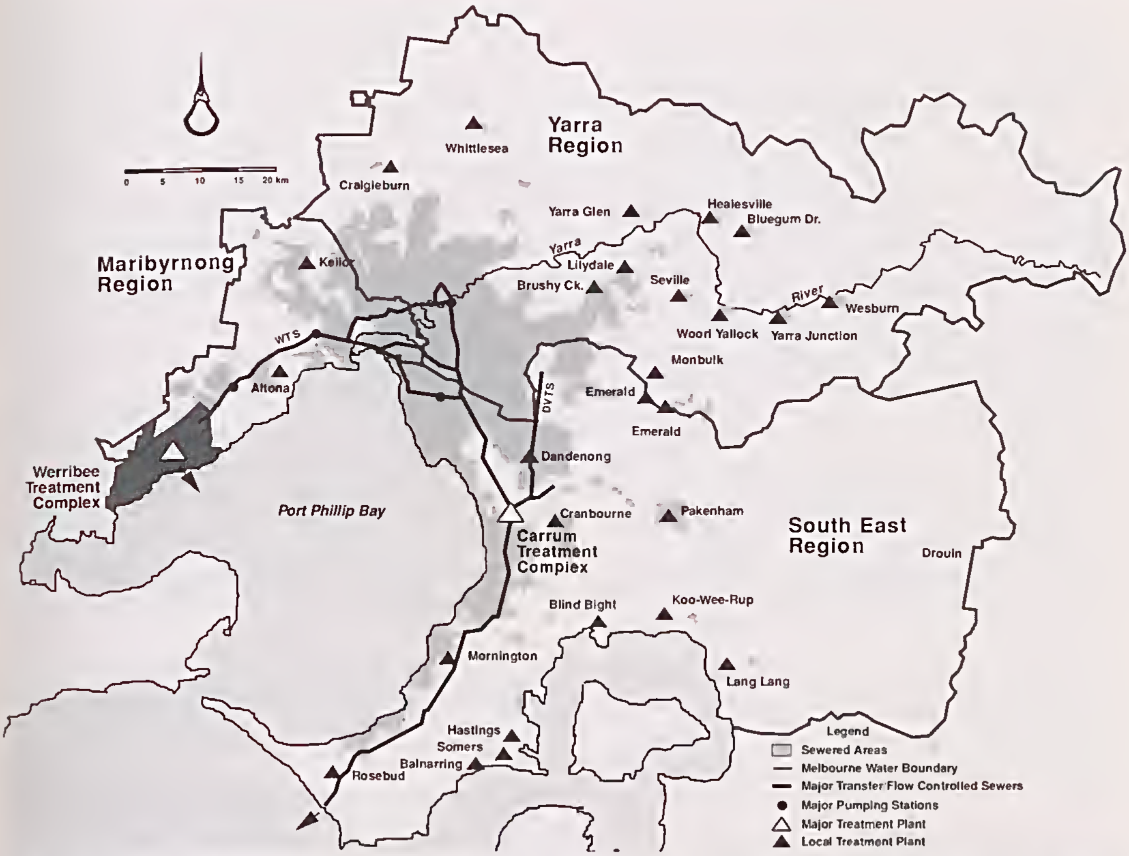

Fig. 1. Schematic plan of the Melbourne sewerage system showing the location of the major trunk sewers, treatment plants and outfalls. The Melbourne Water boundary for the provision of sewerage is also shown.

land filtration, 26% by grass filtration and 58% by lagoons (Croxford 1978, McPherson 1979, Bremner & Chiffings 1991).

Land treatment methods have been used at the WTC to process waste water since 1897, with the final effluent being discharged to Port Phillip Bay for the full 93 year period. We have estimated that a total volume of 9.6 billion ML of sewage has been received at the WTC over this period, during which the population of Melbourne has grown some six fold.

Present preliminary estimates have placed surface nutrient loads from WTC as ranging between 54% and 71% of the total surface loads to the Bay, depending on fluctuations in loads from some stream catchments (Fig. 2).

In addition, Port Phillip Bay receives nutrients from:

(a) Stormwater run-off from Melbourne and its suburbs via drains and input streams; e.g. the Yarra River and its urban drains;

(b) Surface and groundwater run-off from agricultural land in the river and stream catchments;

(c) Atmospheric sources, both particulate and in solution.

Aerial loadings are significant. Carnovale & Saunders (1988) estimated that a total of 0.8–1.3 kilotonnes of N are deposited to the Bay annually from these sources, equivalent to 20–32% of the N load from the WTC.

SCIENTIFIC STUDIES ON PORT PHILLIP BAY

First attempts to obtain a biological survey of the Bay came from the Council of the Royal Society of Victoria who in 1888 elected a Committee which was granted an initial sum of £50 (approximately $3,000 June 1990 equivalent) for the task. A full report of the committee's activities was given in the Society's 1890 Annual

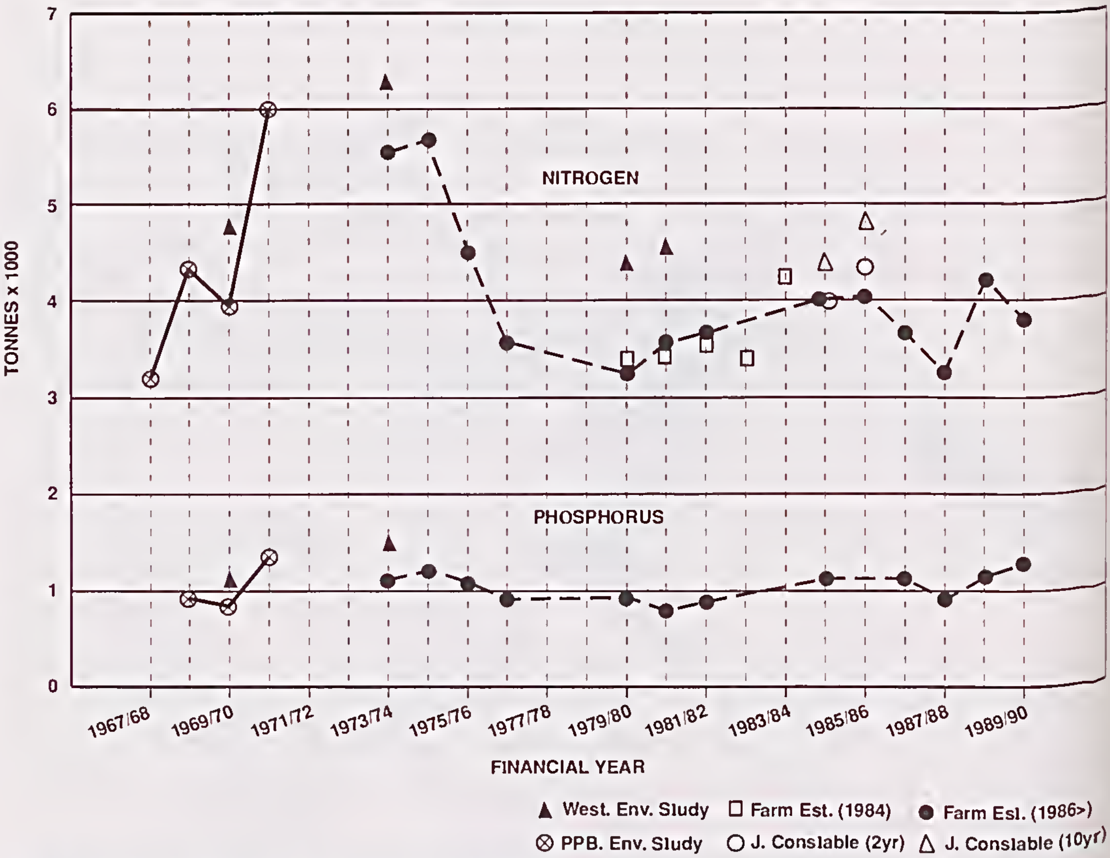

Fig. 2. Annual estimates of total nitrogen and total phosphorus loads discharged from the Werribee Treatment Complex to Port Phillip Bay over the last 20 years. Details of how estimates were derived are given in the Appendix.

Report. The work concentrated on specific taxonomic groups and several monographs were produced, but by 1896 the Society's records did not reflect any on-going work (Macpherson & Lynch 1966). While recognizing the considerable advances made in the collection, taxonomy and naming of species in recent years, a review of this very early work may provide insights into the impact of European settlement on the Bay over the last 100 years.

The first attempt at gaining a systems oversight into the Bay was undertaken by D. J. Rochford between 1947 and 1952 as part of an Australia-wide investigation of the physical processes of coastal embayments and estuaries. Data on chlorinity, temperature, nitrate nitrogen, inorganic phosphates and oxygen were collected from 6 stations around the Bay (Rochford 1966).

No other systematic attempt was made to study the Bay until 1957 when a five-year joint project was undertaken by the National Museum of Victoria and the Fisheries and Wildlife Department, the aim being "... to record the macro flora and fauna and to plot its distribution and where possible at least make an assessment of the density of the population present" (Macpherson & Lynch 1966). The results, published in *Memoirs of the National Museum of Victoria* volumes 27 (1966) and 32 (1971), included papers on geology, geomorphology, bottom sediments, and hydrology (Rochford's work), fisheries and various taxonomic groups. With the exception of Rochford's work, these studies did not assess water quality of the Bay or the overall state of its biological communities.

During 1968–71 the MMBW and the Fisheries and Wildlife Department jointly conducted the first comprehensive environmental study of the Bay and its catchment, in order to determine the relationships between prevailing inputs and conditions in the Bay (*Environmen-*

tal Study of Port Phillip Bay Phase I). The study was to also collect baseline data in the vicinity of the outfall of the proposed south-eastern system sewage treatment plant at Carrum, which was designed to discharge effluent into the Bay for the first ten years of its life, at a site approximately 3.2 km offshore from the Paterson River. The need to address the possible impact of the sewerage discharge was abdicated when in early 1969 the State Government directed that a pipeline to Bass Strait should be included in the construction of the plant (Dingle & Rasmussen 1991). The study continued, however, and was the first of several such studies undertaken in Victoria on different water bodies.

The results of the Phase I Study were summarised in a single publication (MMBW/FWD 1973) but the original data were never collated and many of them have been lost, defeating one of the principal objectives of the study.

For nutrient impacts on the Bay the Port Phillip Bay Phase I Study concluded that:

> Taken as a whole, Port Phillip Bay, is . . . a relatively unpolluted body of water . . . Although nutrient concentrations are relatively high in the waters surrounding the sites of major inputs, extensive mixing in the immediate vicinity of the inputs diminishes concentrations rapidly.
>
> Some nutrients occur at higher concentrations in the Bay than in Bass Strait, suggesting that a potential exists for high biological productivity in the Bay. Compared with polluted estuaries in various parts of the world, however, the abundance of plant and animal plankton (minute floating organisms) in the Bay is generally low.

A second phase of the Study (1975–1980) to some extent addressed questions raised by Phase I regarding the capacity of Port Phillip Bay to sustain waste loads from the urban and industrial growth of Melbourne. Work was undertaken to determine the local effects of the WTC discharges, but this work did not have the same level of integration as the Phase I Study, and the only overviews generated were by Axelrad et al. (1981) and Kelly et al. (1987).

Melbourne Water subsequently commissioned a review of the Phase II Study (Newell 1990) as part of a comprehensive appraisal of the effects of the WTC nutrient discharges on the ecology of the Bay. Newell concluded that

> . . . the level of primary plant production in Port Phillip Bay is in equilibrium between ammonia input and a continual loss of DON (dissolved organic nitrogen). Most input nitrogen is therefore exported as DON to Bass Strait, although some DON may also be recycled.

Newell also stated that primary production is frequently controlled by light availability and mixing rates of Bay waters, rather than by nutrient availability. This finding is consistent with the conclusions of Axelrad et al. (1981).

Following the declaration of the SEPP for the Waters of Port Phillip Bay in 1975, a series of water quality monitoring programs were commissioned by the EPA. The results are reviewed by Longmore (1992) who concludes that the data do not enable the determination of changes in the nutrient status of the Bay over the last 15 years. This is despite a diversion of one-third of Melbourne's sewage to the South Eastern Treatment Complex in 1975. Over the three year period from 1975 to 1977 loads of nitrogen from the WTC were reduced by approximately 45%, from 6,200 tonnes of nitrogen per year to 3,500 tonnes per year. Unfortunately no specific studies were undertaken at the time to determine the impacts on the Bay of this substantial reduction in nutrient loads. Since 1977 loads have increased to approximately 4,000 tonnes of nitrogen per year (Fig. 3).

In 1987 a third phase of the Study was instigated, also with an emphasis on nutrients, but it languished after a period due to insufficient funding. The only projects completed were an investigation commissioned by Melbourne Water on the status of dissolved oxygen in the deep, central region of the Bay, undertaken by the Marine Science Laboratories (Mickelson 1990), and a review by MMBW of historical chlorophyll *a* data for the Bay (Brown 1989).

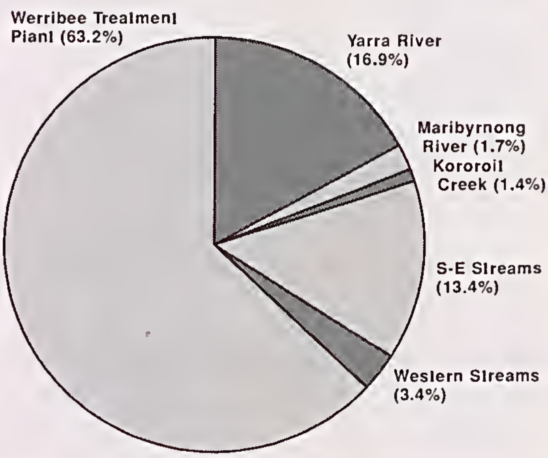

Fig. 3. Proportion of annual total nitrogen loads to Port Phillip Bay for 1980 from major surface inputs, including the Werribee Treatment Complex. Source: EPA Bulletins.

A proposal in 1990 by Melbourne Water to investigate the impact of nutrient loads from all sources on the western side of Port Phillip Bay was subsequently modified by an inter-agency technical committee (MMBW, EPA and the Victorian Department of Conservation and Environment) to address the entire Bay. A systems approach was proposed to provide a much improved understanding of the physical processes and nutrient dynamics, with the aim of developing a nutrients management plan for the Bay which would be effected as a schedule in the SEPP. The proposal failed to win management support, however, due to the perceived high costs involved.

In June 1991 the Minister for Conservation and Environment, Mr Steve Crabb, announced a major environmental study of Port Phillip Bay which is expected to set the agenda for environmental management of the Bay catchment for the next 20 years. The study will commence in June 1992 and will take 4 years to complete at a cost of up to $12 million. In July 1991 Melbourne Water, on behalf of the Study Management Committee (representing Melbourne Water, Department of Conservation and Environment, Environment Protection Authority and Port of Melbourne Authority), commissioned CSIRO to prepare a study design.

The management-based study objectives were evaluated to establish the scientific questions to be answered for both nutrient and toxicant issues. While recognizing that past and present work must be reviewed and integrated into the new research, scientific tasks have been defined which include a comprehensive understanding of the physical processes influencing transport, distribution and mixing of discharged materials; determination of nutrient and toxicant loads from inputs, their status in water and biota, and key transformation processes; and the role of sediments as storage reservoirs and as sites for transformation processes.

PLANNING FOR THE SUSTAINABLE DEVELOPMENT OF PORT PHILLIP BAY

While planning in Melbourne to date has been effective in minimising adverse environmental impacts on Port Phillip Bay, as Melbourne's size increases its supporting infrastructure must be augmented and improved to ensure that detrimental impacts are minimised.

The effects of present nutrient additions on the Bay remain largely unknown. Recent reviews of chlorophyll *a* data (a measure of phytoplankton biomass) collected over the period 1969–1986 has shown that there have been statistically significant measurable increases in several of the segments but not over the entire Bay (Brown 1989, Saunders & Goudey 1990). In those segments where the increase is measurable it is not considered to be alarming (Brown 1989). Even so, concerns have been raised as to the present condition of Port Phillip Bay. Events that have been cited as causes for concern include the following.

(a) Local episodes of reduction in dissolved oxygen concentrations have been measured recently in the bottom waters of the Bay (Axelrad 1986, Mickelson 1990). It is not known whether the frequency and extent of these events are unusual for the Bay. Similar conditions have been raised as a cause for concern in comparable coastal systems elsewhere (Leffler 1990).

(b) Phytoplankton blooms are reported to have been observed as isolated occurrences although it is not documented as to where, when or how often. Phytoplankton blooms in coastal waters and embayments are very much a natural occurrence (Harris 1986), and quite high concentrations of chlorophyll *a* were reported during the extensive sampling program undertaken during the Phase I study (up to 20 mg/m^3).

(c) Blooms of toxic phytoplankton have been observed, particularly in the northern part of the Bay, and on at least one occasion associated with mortality of fish and shellfish (Arnott 1990). Although it is thought that blooms of these organisms are not a response to the input of nutrients from the WTC, they may nevertheless be important indicators of changing conditions in Port Phillip Bay.

(d) Reduction in seagrass density was measured during 1986 in the Geelong Arm, compared with measurements taken in 1981 (unpublished data, Marine Science Laboratories). While such reductions elsewhere have been shown to be a result of nutrient enrichment (Cambridge et al. 1986, Simpson et al. 1990), we do not know whether this is the case in Port Phillip Bay.

(e) Public concern persists over seaweed "washup" on metropolitan beaches. It has not been established whether seaweed biomass has increased over time in Port Phillip Bay, but if so it is important to establish the cause, and nutrient loads is one of the factors that would have to be considered.

Whether or not these matters are truly of concern and are a product of nutrient addition to the Bay, the problem remains that as the population of Melbourne increases a point will be reached where the Bay will not be able to assimilate increased nutrient loads without major changes in ecosystem function and water quality. It is important that we determine in a scientific manner what are the acceptable loads, and that we build these into our strategic planning. This, in part, is the intention of the present study. The scientific information must, however, be considered in context with economic, social and engineering factors.

Provision of sewerage services to a large city like Melbourne requires long-term planning (up to 50 years) to ensure that the required capital works are put in place and that the very large costs (hundreds of millions of dollars) are spread over a number of generations. Cost estimates of four future development options for the WTC are listed in Table 1. A decision to upgrade the treatment facilities and to divert the discharge to Bass Strait (option 4) may result in an increase in the annual operating cost for the WTC of $145 million, $100 million of which would go to interest payments on the loans required to finance the capital works program. The cost to the community of some of these options represents not only an economic debt but also an opportunity cost, both in financial terms and in use of natural resources. That is, not only is the option lost to spend the money on other community needs such as education or health care, but the possibility also exists of imposing unnecessary environmental impacts outside Port Phillip Bay.

It is therefore important that decisions on the provision of infrastructure to the city take into account all of the costs, options and consequences—environmental as well as economic and social. We believe the only successful way to ensure that this objective is met is through the development of a fully integrated waste disposal strategy for Melbourne, including a nutrient management plan for Port Phillip Bay and its catchment. This plan, which must be based on a sound scientific knowledge of the systems impacted, requires the integration of State policies and State environmental management initiatives with Melbourne Water's development strategies and with the implementation programs of other service agencies. Future plans by industry must also be considered.

System	Capital $M	Operating $M
Modified existing lagoon and land treatment system	120	20
Conventional primary treatment, improved lagoon and land treatment	260	35
Conventional primary and secondary treatment, improved lagoon and land treatment	480–540	40–45
Conventional primary and secondary treatment with ocean outfall	790–850	45

Table 1. Approximate capital and operating costs of major basic elements of future development options for the WTC. Factors such as interest and redemption capital borrowings are not included. Costs relate to predicted development with a dry weather flow of about 750 ML/day and are in 1987 $ values. Source: Stage 2 Summary Report, Werribee Treatment Complex Development Strategy, Board of Works, 1989.

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APPENDIX

A number of estimates of nutrient loads from the WTC to Port Phillip Bay have been made over the last 20 years. A brief description of how these estimates were derived is given below.

1. *PPB Environmental Study, Phase I, 1973.* The loads calculated during this study are based on monthly grab samples of effluent analysed for nutrient concentrations, and outflow rates for WTC discharge drains estimated by WTC personnel calibrated to measurements by a Gurley propeller-type current meter. The period of measurements was from 1968–1971.

2. *Western Environmental Study, 1977.* (D. Lynch, P. Scott & J. Constable, unpublished report, Melbourne Water. Loads were calculated using influent sewage volumes and nutrient concentrations, and estimated loading removal rates of WTC treatment processes. This was done for the periods 1969/70, 1973/4, 1979/80, 1980/81, 1984/85, 1985/86.

3. *WTC ("Farm") estimates, 1984.* Loads were calculated using weekly grab samples of effluent analysed

for nutrient concentrations, and outflow rates adjusted to 1983/84 percentage inflows processed through to particular outlets. There is some doubt about 1983/84 outflow measurements.

4. *WTC ("Farm") estimates, 1986 >*. Loads were calculated using monthly grab samples of effluent (1973/74–1975/76) and weekly grab samples (1976/77–1981/2) analysed for nutrient concentrations, and outflow rates adjusted to 1984/85–1985/86 percentage inflows processed through to particular outlets. The 1984/85 and 1985/86 loads are based on continuous flow monitoring at each outlet and weekly grab samples of effluent analysed for nutrient concentrations at all five EPA licensed outlets.

5. *J. Constable (2 year), 1987*. Loads were calculated by estimating the N discharge rate to the Bay as the difference between the nitrogen mass load delivered to the WTC annually and the estimated nitrogen removal rates of the different treatment processes. A two year average of monthly sampled total N concentrations of 58 mg/L for influent was used. The two year period used is not documented.

6. *J. Constable (10 year), 1987*. Loads were calculated by estimating the N discharge rate to the Bay as the difference between the nitrogen mass load delivered to the WTC annually and the estimated nitrogen removal rates of the different treatment processes. A ten year average of monthly sampled total N concentrations of 62 mg/L for influent was used. The ten year period used is not documented.